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VARIATION OF *P*-WAVE VELOCITY BEFORE AND AFTER THE GALWAY LAKE EARTHQUAKE ($M_L = 5.2$) AND THE GOAT MOUNTAIN EARTHQUAKES ($M_L = 4.7, 4.7$), 1975, IN THE MOJAVE DESERT, CALIFORNIA

BY HIROO KANAMORI AND GARY FUIS

ABSTRACT

Since June 1973, the California Institute of Technology Seismological Laboratory has been monitoring quarry blasts in southern California for the purpose of detecting possible velocity changes before earthquakes. On June 1, 1975, an $M_L = 5.2$ earthquake occurred near Galway Lake, about 60 km southeast of Barstow, California. On November 15, 1975, and December 14, 1975, $M_L = 4.7$ earthquakes occurred about 30 km southeast of Galway Lake near Goat Mountain. These three epicenters are close to Hector and Victorville quarries, which have been monitored by CIT.

First-motion data, the distribution of aftershocks, and ground breakage associated with the Galway Lake earthquake indicate right-lateral strike slip on a fault striking N20°W, dipping 70° SW. First-motion data and the distribution of aftershocks for the first Goat Mountain earthquake indicate normal dip slip on a plane striking north-northeast, dipping about 60° to the west-northwest.

Blasts at Hector and Victorville quarries were timed with an accuracy of ± 0.01 sec, and first arrivals at a number of stations of the USGS-CIT network can be read to an accuracy of ± 0.02 sec. The data are plotted in terms of residuals versus time at each station in such a fashion as to reflect trends in velocity. Origin times of all earthquakes $\gtrsim 4.0$ in our study area are plotted on these curves.

The most important results of this study are observations that are "negative" in character. These observations are: (1) no changes greater than about 0.1 sec (or about 1 per cent in average velocity) are seen at any station during the 2-year period of this study, (2) given the flatness of the curves, it is difficult to draw correlations between any larger earthquakes and changes in velocity. In particular, no unique change is seen before the Galway Lake earthquake along two paths that cross the epicentral region of this earthquake at right angles to each other. The data are such that only an anomaly less than 2 months in duration could have escaped detection. Similarly, no unique change is seen before the Goat Mountain earthquakes along two subparallel paths through the epicentral area. Only an anomaly less than 1 month in duration could have escaped detection.

One observation that is "positive" in character can be made from the curves; namely, slight but systematic changes in velocity can be seen. For Hector blasts, most stations show a systematic increase in velocity with time of as much as 0.8 per cent. For Victorville blasts, most stations show an opposite trend.

The results of this study are somewhat disappointing from the point of view of the standard dilatancy model, which predicts a 10 to 20 per cent decrease in *P* velocity over an area of several source dimensions in diameter before an earthquake. Before the $M_L = 5.2$ Galway Lake earthquake, this decrease should occur over an area about 30 km in diameter over a period of 3 to 6 months. Before the Goat Mountain earthquake, this decrease should have occurred over an area about 20 km in diameter over a period of 2 to 4 months. Our data preclude the possibility of precursory changes this large before these earthquakes. It is still possible that dilatancy

accompanied these earthquakes, but the effect must have been small. It is also possible that these earthquakes are not representative of other M_L = 4.7 to 5.2 earthquakes; however, at least two different types of faulting are represented, namely strike slip and normal faulting.

The small systematic changes in velocity that are seen may have one of the following explanations: (1) there were systematic variations in local delays at the two quarries, or (2) there were regional changes in crustal velocity. The fact that shot points migrated in more or less systematic fashions in both Hector and Victorville quarries during the period of this study suggests that the first explanation may be correct. The second explanation is intriguing, but the opposite trends for the Hector and Victorville data are somewhat puzzling, unless adjacent regions, one surrounding Hector quarry and one surrounding Victorville quarry, are simultaneously undergoing opposite changes in velocity. This possibility is difficult to evaluate. One can observe, however, that during the 2-year period of this study, all larger earthquakes were concentrated in the region of the Hector quarry, and there was simultaneously an absence of larger earthquakes in the region of the Victorville quarry. Perhaps the occurrence of larger earthquakes is related to rising velocities near Hector, if they are indeed rising. Such a correlation is reasonable if the velocity increase is due to tectonic stress loading.

INTRODUCTION

Since June 1973, the Seismological Laboratory of the California Institute of Technology (CIT) has been monitoring blasts for the purpose of detecting possible velocity changes prior to earthquakes (Kanamori and Hadley, 1975). Although precursory velocity change has been reported for many events, (e.g. Kondratenko and Nersesov, 1962; Semenov, 1969; Aggarwal *et al.*, 1973; Whitcomb *et al.*, 1973; Stewart, 1973; Ohtake 1973; Wyss and Johnston, 1974; Robinson *et al.*, 1974; Wyss, 1975), several negative, or nonpositive, cases also have been reported (McEvilly and Johnson, 1973; Allen and Helmberger, 1973; Cramer and Kovach, 1974; Boore *et al.*, 1975). Several important questions still remain to be answered before we can adopt velocity change as a useful predictive element of earthquakes: (1) do detectable velocity changes precede earthquakes? (2) If so, do these changes precede all types of earthquakes, e.g., strike-slip, thrust, normal, intraplate, interplate? (3) In cases where changes are observed, what is the size of the anomalous area with respect to the characteristic dimension of the source, such as the fault length and the aftershock area? (4) In these cases, can the precursor time interval be related to the earthquake magnitude by a more or less universal relation? One of the chief objectives of Caltech's project is to obtain data to answer these questions in as definitive a way as possible. In view of the relatively large temporal and geographic spacing involved in our experiment (typically, there is one data point every 2 to 3 months, and source distances are of the order of 15 to 100 km), we are primarily concerned with relatively large earthquakes, e.g., $M_L \gtrsim 6.5$; smaller events may escape observation. The recent installation of USGS stations in southern California has, however, enhanced the applicability of this monitoring system to smaller events.

On June 1 (May 31, P.D.T.), 1975, a M_L = 5.2 earthquake occurred near Galway Lake, about 60 km southeast of Barstow, California (Figure 1); this is the largest event to occur in our network since the program was initiated in 1973. Fortunately, four quarry blasts at Hector, California, about 25 km to the north of the epicenter and three blasts at Victorville, California, about 60 km to the west of the epicenter, had been timed with an accuracy of $\pm$ 0.01 sec before the earthquake, the last blast being 3 weeks before the earthquake. A number of seismic stations of the USGS-CIT southern California network recorded these blasts at distances of 37 to 160 km with a timing error as little as $\pm$ 0.02 sec.

The pre-earthquake data at these stations did not show any marked velocity change. Since the data are uncommonly precise, however, we have made a more thorough investigation of the records. We have also continued to monitor the quarries at Hector and Victorville to determine if any change followed the earthquake.

On November 15, 1975 and on December 14, 1975, earthquakes of magnitude $M_L = 4.7$ each occurred approximately 30 km southeast of Galway Lake near Goat Mountain. As in the case of the Galway Lake earthquake, no marked velocity changes were seen before these earthquakes.

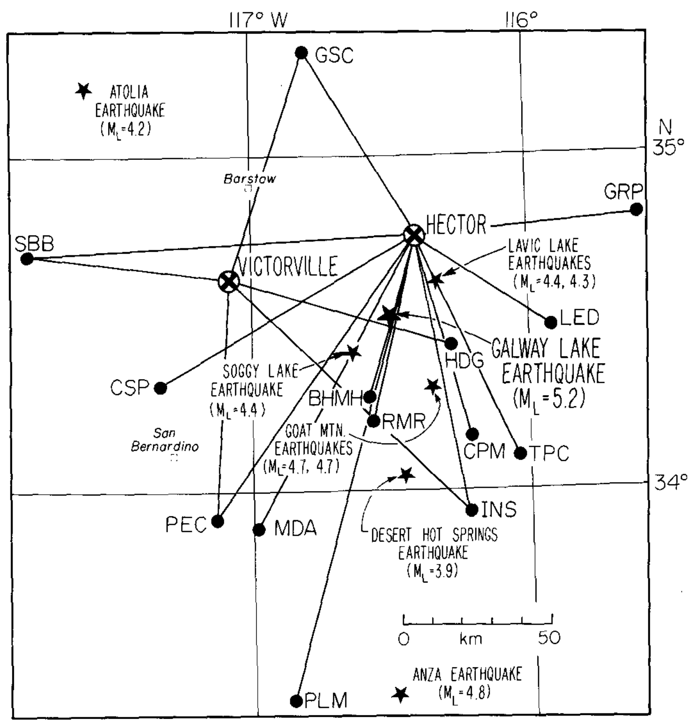

FIG. 1. Location of shot points, USGS-CIT seismic stations, and epicenters of earthquakes $\gtrsim 4.0$ that occurred between June 26, 1974 and April 2, 1975 within the area of the figure.

Data and Results

The first-motion data for the Galway Lake earthquake indicate a strike slip on a plane striking N20°W, dipping 70°SW (right-lateral) or N70°E (left-lateral). After the earthquake, a narrow zone of ground breakage was discovered that extends about 5 km in a N16°W direction. A maximum right-lateral offset of 18 mm was observed on some of the cracks in this zone (G. Fuis and C. R. Allen, personal communication, 1975). The aftershock area has roughly the same trend and linear extent as the zone of ground breakage. A source dimension of 5 km, typical of a $M_L = 5.2$ earthquake (e.g., Wyss and Brune, 1968), is suggested. Nearly all aftershocks are shallower than 5 km, as determined from portable instruments in the epicentral area indicating that the source region of this earthquake involves the uppermost part of the crust.

First-motion data for the first Goat Mountain earthquake on November 15, 1975, indicate largely normal dip slip on either a plane striking approximately north-south and dipping about 60° west or a plane striking approximately N50°E and dipping about 60° southeast. Aftershocks are clustered in a zone 10 to 15 km long that has a north-northeast

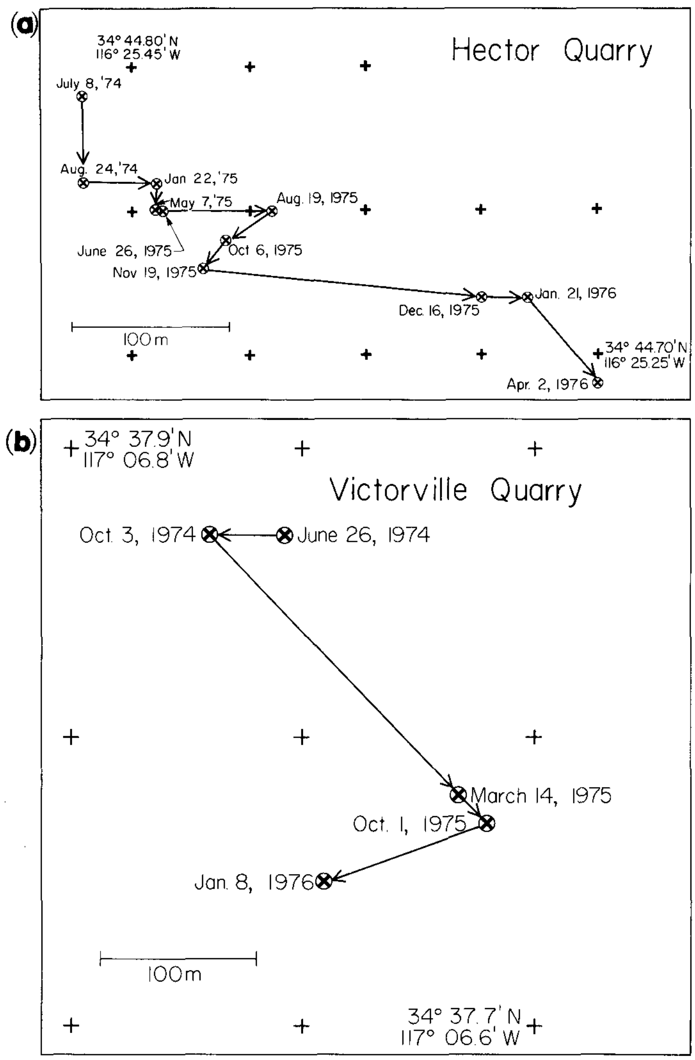

FIG. 2. Locations of shot points in Hector quarry (a) and Victorville quarry (b). Arrows show succession of shot points.

trend, supporting a focal mechanism of normal dip slip on a north-south plane. Depths for most aftershocks, determined with the aid of a portable instrument within 2 km of many epicenters, range from 6 to 10 km. First-motion data for the second Goat Mountain earthquake, on December 14, 1975, indicate a focal mechanism similar to that of the Galway Lake earthquake, but rotated slightly counterclockwise; vertical planes strike N30°W and N60°E. Epicenters for aftershocks are too tightly clustered to indicate a fault plane. Depths range from 2 to 10 km.

Quarry blasts used in this study occurred over a span of nearly 2 years from June 26, 1974 to April 2, 1976. All blasts were timed with 0.01 sec accuracy by using a disposable pick-up placed next to the first explosive hole to be fired in the blast pattern. Delays in the blast patterns ranged from a total of 0.00 sec to a total of 0.05 sec for Hector blasts; no delays were used in the Victorville blasts. Dimensions of the blast patterns were typically 7 by 50 meters. Blast locations in Hector quarry migrated more or less systemati-

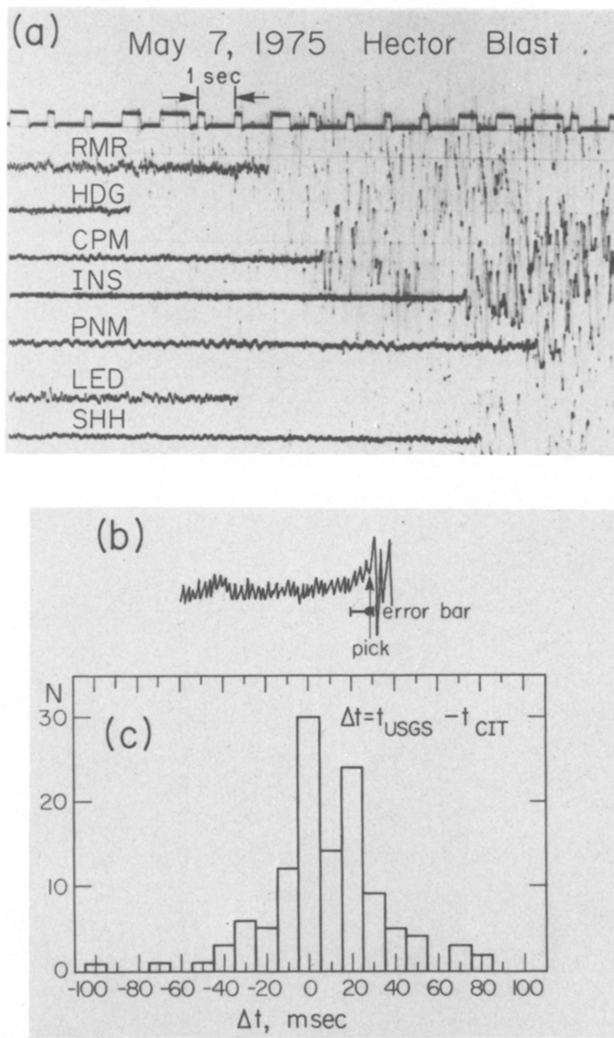

FIG. 3. Develocorder record of a Hector blast on May 7, 1975 (a), a sketch in which our method of determining error bars is shown (b), and a histogram showing the time difference between USGS and CIT readings (c).

cally from northwest to southeast with a maximum separation of about 380 meters (Figure 2a). In Victorville quarry, blast locations also migrated more or less systematically southeastward with a maximum separation of about 230 meters (Figure 2b).

The signals from the blasts were recorded at a number of stations in the USGS-CIT network (Figure 1). Data from these stations are telemetered to Pasadena and recorded on Develocorder films, together with WWVB radio signals. When the onset of the signal from a blast is very sharp, it can be read with an accuracy of 0.01 to 0.02 sec (Figure 3a).

TABLE 1

HECTOR BLASTS

Station	Distance, Δ (km)	Azimuth (deg)	Travel time, t (sec)		Residual, Δt (sec)		Remark
July 8, 1974; 34°44.79′N, 116°25.47′W; $23^h40^m35.63^s$ GMT; 23 KLB; 10 delays @ 5 msec							
BHMH	54.75	199	9.99	+0.03 −0.10	0.03	+0.03 −0.10	
RMR							Dead
INS	92.40	167	16.17	+0.02 −0.04	0.02	+0.02 −0.04	
HDG	36.91	163	7.27	+0.02 −0.05	0.22	+0.02 −0.05	
CPM							Dead
TPC	79.02	154	14.17	±0.10	0.22	±0.10	
LED	54.41	125	10.18	±0.02	0.26	±0.02	
GRP	75.33	85	13.37	±0.02	0.02	±0.02	
GSC	70.71	331	12.91	±0.05	0.32	±0.05	
SBB	128.45	267	22.06	+0.05 −0.08	0.00	+0.05 −0.08	
CSP	98.92	240	17.28	+0.10 −0.07	0.06	+0.10 −0.07	
PEC	116.49	216	20.19	±0.03	0.09	±0.03	Polarity reversed
MDA							Dead
PLM	159.72	195	27.10	+0.08 −0.10	0.94	+0.08 −0.10	
August 24, 1974; 34°44.76′N, 116°25.47′W; $00^h03^m06.38^s$ GMT; 22 KLB; 5 delays @ 5 msec							
BHMH	54.70	199	10.01	+0.03 −0.05	0.04	+0.03 −0.05	
RMR							Dead
INS	92.35	167	16.19	+0.02 −0.05	0.05	+0.02 −0.05	
HDG	36.85	163	7.24	±0.02	0.20	±0.02	
CPM	68.93	162	12.41	+0.02 −0.04	0.11	+0.02 −0.04	
TPC	78.97	154	14.24	+0.10 −0.15	0.29	+0.10 −0.15	
LED							Dead
GRP							Dead
GSC	70.75	331	12.94	+0.05 −0.12	0.34	+0.05 −0.12	
SBB	128.45	267	22.07	±0.04	0.01	±0.04	
CSP							Dead
PEC	116.45	216	20.19	+0.02 −0.05	0.10	+0.02 −0.05	
MDA							Dead
PLM	159.66	195	27.05	+0.14 −0.20	0.89	+0.14 −0.20	
January 22, 1975; 34°44.76′N, 116°25.44′W; $00^h43^m08.01^s$ GMT; 32 KLB; no delays							
BHMH							Dead
RMR	60.76	193	10.90	±0.02	−0.06	±0.02	
INS	92.34	167	16.13	±0.02	−0.01	±0.02	

TABLE 1—*Continued*

Station	Distance, Δ (km)	Azimuth (deg)	Travel time, t (sec)		Residual, Δt (sec)		Remark
HDG	36.84	163	7.21	±0.02	0.17	±0.02	
CPM	68.91	162	12.31	±0.02	0.01	±0.02	
TPC	78.95	154	14.16	±0.05	0.22	±0.05	
LED	54.34	125	10.09	±0.03	0.18	±0.03	
GRP	75.29	85	13.31	±0.02	−0.03	±0.02	
GSC	70.78	331	12.84	±0.08	0.24	±0.08	
SBB	128.50	267	22.02	+0.03	−0.04	+0.03	
				−0.13		−0.13	
CSP	98.93	240	17.31	+0.02	0.09	+0.02	
				−0.05		−0.05	
PEC	116.48	216	20.14	±0.02	0.05	±0.02	Polarity reversed
MDA	106.51	210	18.53	+0.06	0.07	+0.06	Polarity reversed
				−0.06?		−0.06?	
PLM	159.68	195	27.05	±0.08	0.89	±0.08	
May 7, 1975; 34°44.75′N; 116°25.44′W; $23^h49^m00.99^s$ GMT; 18 KLB; 2 delays @ 9 msec							
BHMH							Dead
RMR	60.74	193	10.91	+0.02	−0.05	+0.02	
				−0.03		−0.03	
INS	92.32	167	16.13	+0.03	0.00	+0.03	
				−0.06		−0.06	
HDG	36.82	163	7.20	+0.02	0.16	+0.02	
				−0.03		−0.03	
CPM	68.90	162	12.34	±0.02	0.05	±0.02	
TPC	78.93	154	14.12	±0.05	0.18	±0.05	
LED	54.33	125	10.09	+0.02	0.18	+0.02	
				−0.04		−0.04	
GRP	75.29	85	13.31	+0.05	−0.03	+0.05	
				−0.03		−0.03	
GSC	70.79	331	12.92	±0.05	0.31	±0.05	
SBB	128.50	267	21.98	±0.03	−0.08	±0.03	
CSP							Dead
PEC	116.46	216	20.06	±0.05	−0.03	±0.05	
MDA							Noisy
PLM	159.66	195	27.06	±0.10	0.90	±0.10	
June 26, 1975; 34°44.75′N; 116°25.44′W; $23^h47^m16.61^s$ GMT; 20 KLB; 2 delays @ 9 msec							
BHMH							Dead
RMR	60.74	193	10.89	+0.02	−0.07	+0.02	
				−0.05		−0.05	
INS	92.32	167	16.19	+0.08	0.06	±0.05	Weak; polarity reversed
				−0.15			
HDG	36.82	163	7.18	±0.02	0.14	±0.02	
CPM	68.90	162	12.29	±0.04	0.00	±0.04	
TPC	78.93	154	14.14	+0.07	0.20	+0.07	
				−0.12		−0.12	
LED	54.33	125	10.10	±0.02	0.19	±0.02	
GRP	75.29	85	13.31	+0.02	−0.03	+0.02	
				−0.06		−0.06	
GSC	70.79	331	12.88	+0.12	0.27	+0.12	
				−0.10		−0.10	
SBB	128.50	267	21.99	±0.03	−0.07	±0.03	

TABLE 1—*Continued*

TABLE 1—*Continued*

Station	Distance, Δ (km)	Azimuth (deg)	Travel time, t (sec)		Residual, Δt (sec)		Remark
CSP	98.92	240	17.31	+0.03 −0.13	0.09	+0.03 −0.13	
PEC	116.46	216	20.09	+0.03 −0.06	0.00	+0.03 −0.06	
MDA	106.44	210	18.67	+0.03 −0.10	0.21	+0.03 −0.10	
PLM	159.66	195	27.05	+0.10 −0.20	0.89	+0.10 −0.20	
August 19, 1975; 34°44.74′N; 116°25.39′W; $23^h30^m52.21^s$ GMT; 38 KLB; 2 delays @ 9 msec							
BHMH	54.70	199	9.95	±0.02	−0.02	±0.02	
RMR	60.74	193	10.91	±0.02	−0.05	±0.02	
INS	92.28	167	16.12	±0.03	−0.01	±0.03	
HDG	36.78	163	7.18	±0.02	0.15	±0.02	
CPM	68.85	162	12.35	+0.02 −0.10	0.06	+0.02 −0.10	
TPC	78.88	154	14.12	+0.03 −0.05	0.19	+0.03 −0.05	
LED	54.25	125	10.07	±0.02	0.18	±0.02	
GRP	75.22	85	13.28	+0.02 −0.05	−0.05	+0.02 −0.05	
GSC	70.84	331	12.84	±0.10	0.23	±0.10	
SBB	128.57	267	22.01	+0.02 −0.03	−0.07	+0.02 −0.03	
CSP							Dead
PEC	116.49	216	20.09	±0.03	−0.01	±0.03	Polarity reversed
MDA	106.51	210	18.69	+0.02 −0.11	0.23	+0.02 −0.11	
PLM	159.66	195	26.95	+0.13 −0.15	0.79	+0.13 −0.15	
October 6, 1975; 34°44.74′N; 116°25.41′W; $01^h15^m15.80^s$ GMT; 17 KLB; 2 delays @ 9 msec							
BHMH							Dead
RMR	60.73	193	10.91	±0.03	−0.05	±0.03	
INS							Dead
HDG	36.79	163	7.21	±0.02	0.18	±0.02	
CPM	68.86	162	12.37	±0.02	0.08	±0.02	
TPC	78.90	154	14.12	+0.03 −0.06	0.19	+0.03 −0.06	
LED	54.28	125	10.11	±0.02	0.21	±0.02	
GRP	75.25	85	13.29	±0.03	−0.05	±0.03	
GSC	70.83	331	12.95	+0.03 −0.08	0.34	+0.03 −0.08	
SBB	128.54	267	22.00	±0.03	−0.07	±0.03	
CSP	98.95	240	17.29	±0.04	0.07	±0.04	
PEC	116.47	216	20.12	+0.02 −0.03	0.03	+0.02 −0.03	Polarity reversed
MDA	106.50	210	18.73	±0.03	0.27	±0.03	
PLM	159.65	195	27.08	+0.05 −0.10	0.92	+0.05 −0.10	

TABLE 1—*Continued*

Station	Distance, Δ (km)	Azimuth (deg)	Travel time, t (sec)		Residual, Δt (sec)		Remark
November 19, 1975; 34°44.73′N; 116°25.42′W; 01ʰ01ᵐ08.05ˢ GMT; 40 KLB; 2 delays @ 9 msec							
BHMH							Dead
RMR	60.71	193	10.87	+0.03 −0.05	−0.08	+0.03 −0.05	
INS	92.28	167	16.12	+0.05 −0.08	−0.01	+0.05 −0.08	
HDG	36.78	163	7.17	±0.05	0.14	±0.05	
CPM	68.85	162	12.34	+0.03 −0.09	0.05	+0.03 −0.09	
TPC	78.89	154	14.10	±0.05	0.17	±0.05	
LED							Noisy
GRP	75.27	85	13.25	±0.03	−0.09	±0.03	
GSC	70.84	331	12.82	±0.04	0.21	±0.04	
SBB	128.52	267	21.99	+0.02 −0.03	−0.08	+0.02 −0.03	
CSP	98.93	240	17.20	±0.10	−0.02	±0.10	
PEC	116.45	216	20.07	+0.03 −0.04	−0.02	+0.03 −0.04	Polarity reversed
MDA	106.47	210	18.66	+0.02 −0.06	0.21	+0.02 −0.06	
PLM	159.63	195	27.05	+0.08 −0.10	0.90	+0.08 −0.10	
December 16, 1975; 34°44.72′N; 116°25.30′W; 02ʰ34ᵐ09.72ˢ GMT; 22 KLB; 2 delays @ 9 msec							
BHMH							Dead
RMR	60.73	193	10.91	±0.03	−0.05	±0.03	
INS	92.22	167	16.19	+0.03 −0.06	0.07	+0.03 −0.06	
HDG	37.71	163	7.18	±0.02	0.16	±0.02	
CPM	68.78	162	12.35	±0.05	0.07	±0.05	
TPC	78.79	154	14.11	±0.06	0.19	±0.06	
LED	54.12	125	10.10	+0.02 −0.05?	0.23	+0.02 −0.05?	
GRP	75.09	85	13.24	±0.02	−0.07	±0.02	
GSC	70.94	330	12.88	+0.06 −0.05	0.25	+0.06 −0.05	
SBB	128.70	267	22.02	±0.04	−0.08	±0.04	
CSP							Dead
PEC	116.54	216	20.13	+0.03 −0.05	0.03	+0.03 −0.05	Polarity reversed
MDA	106.55	210	18.78	+0.05 −0.20?	0.31	+0.05 −0.20?	Noisy
PLM	159.66	175	27.03	±0.05	0.87	±0.05	
January 21, 1976; 34°44.72′N; 116°25.28′W; 01ʰ22ᵐ34.38ˢ GMT; 22 KLB; 4 delays @ 9 msec							
BHMH							Dead
RMR	60.74	193	10.91	+0.05 −0.06	−0.05	+0.05 −0.06	
INS	92.21	167	16.17	+0.06 −0.04	0.05	+0.06 −0.04	
HDG	36.70	163	7.19	±0.02	0.17	±0.02	

TABLE 1—*Continued*

TABLE 1—*Continued*

Station	Distance, Δ (km)	Azimuth (deg)	Travel time, t (sec)		Residual, Δt (sec)		Remark
CPM	68.77	163	12.34	±0.10	0.07	±0.10	Weak
TPC	78.78	154	14.16	+0.03	0.25	+0.03	
				−0.07		−0.07	
LED	54.09	125	10.02	±0.02	0.15	±0.02	
GRP	75.05	85	13.30	±0.02	0.00	±0.02	
GSC	70.96	330	12.84	±0.08	0.21	±0.08	
SBB	128.74	267	22.02	±0.03	−0.08	±0.03	
CSP	99.11	240	17.33	+0.03	0.08	+0.03	
				−0.04		−0.04	
PEC	116.56	216	20.13	±0.05	0.02	±0.05	Polarity reversed
MDA							Dead
PLM	159.67	195	27.12	±0.10	0.96	±0.10	
April 2, 1976; 34°44.69′N; 116°25.25′W; 00^{h}44^{m}58.47^s GMT; 25KLB; 2 delays, @ 9 msec							
BHMH							Dead
RMR	60.70	194	10.92	+0.02	−0.03	+0.02	
				−0.03		−0.03	
INS	92.15	167	16.20	+0.02	0.09	+0.02	
				−0.07		−0.07	
HDG							Dead
CPM							Weak
TPC	78.71	154	14.10	+0.06	0.20	+0.06	
				−0.10		−0.10	
LED	54.02	125	10.03	±0.02	0.17	±0.02	
GRP							Dead
GSC	71.03	330	12.74	+0.20	0.10	+0.20	
				−0.10		−0.10	
SBB	128.78	267	22.01	±0.06	−0.10	±0.06	
CSP							Noisy
PEC	116.54	216	20.14	±0.03	0.03	±0.03	Polarity reversed
MDA	106.54	210	18.69	+0.05	0.22	+0.05	
				−0.10		−0.10	
PLM	159.62	195	27.10	+0.10	0.95	+0.10	
				−0.20?		−0.20?	

TABLE 2

VICTORVILLE BLASTS

Station	Distance, Δ (km)	Azimuth (deg)	Travel time, t (sec)		Residual, Δt (sec)		Remarks
June 26, 1974; 34°37.87′N; 117°06.71′W; 22^{h}30^{m}25.73^s GMT; 45 KLB; no delays							
INS	114.41	132	19.78	±0.03	0.31	±0.03	
HDG	77.40	107	13.65	+0.02	0.16	+0.02	
				−0.06		−0.06	
GSC	79.49	21	13.90	±0.03	0.07	±0.03	
SBB	65.68	276	11.47	±0.02	−0.10	±0.02	
CSP	43.23	211	7.68	±0.02	−0.21	±0.02	
PEC	82.13	183	14.11	+0.10	−0.15	+0.10	Polarity reversed
				−0.02		−0.02	

TABLE 2—*Continued*

Station	Distance, Δ (km)	Azimuth (deg)	Travel time, *t* (sec)		Residual, Δ*t* (sec)		Remarks
October 3, 1974; 34°37.87′N; 117°06.74′W; $17^h58^m56.60^s$ GMT; 33 KLB; no delays							
INS	114.44	132	19.91	+0.03 −0.07	0.35	+0.03 −0.07	
HDG	77.44	107	13.69	+0.02 −0.03	0.19	+0.02 −0.03	
GSC	79.50	21	13.96	+0.03 −0.05	0.13	+0.03 −0.05	
SBB	65.64	276	11.48	+0.02 −0.03	−0.08	+0.02 −0.03	
CSP	43.20	211	7.65	±0.03	−0.23	±0.03	
PEC	82.13	183	14.24	±0.02	−0.02	±0.02	
March 14, 1975; 34°37.78′N; 117°06.63′N; $23^h00^m07.47^s$ GMT; 44 KLB, no delay							
INS	114.21	132	19.87	+0.03 −0.09	0.35	+0.03 −0.09	
HDG	77.24	107	13.60	±0.02	0.14	±0.02	
GSC	79.60	21	13.93	+0.06 −0.05	0.08	+0.06 −0.05	
SBB	65.82	276	11.53	±0.02	−0.06	±0.02	
CSP	43.15	211	7.73	±0.03	−0.14	±0.03	
PEC	81.97	183	14.23	+0.03 −0.05	−0.01	+0.03 −0.05	
October 1, 1975; 34°37.77′N; 117°06.62′W. $22^h40^m56.99^s$ GMT; 30 KLB, no delays							
INS							Noisy
HDG	77.22	107	13.65	+0.03 −0.05	0.19	+0.03 −0.05	
GSC	79.61	210	14.01	±0.02	0.16	±0.02	
SBB	65.84	276	11.56	±0.02	−0.03	±0.02	
CSP	43.14	211	7.70	±0.03	−0.17	±0.03	
PEC	81.95	183	14.27	+0.02 −0.05	0.04	+0.02 −0.05	Polarity reversed
January 8, 1976; 34°37.75′N; 117°06.69′W; $23^h26^m24.64^s$ GMT; 19 KLB, no delays							
INS	114.24	132	19.89	+0.06 −0.03	0.36	+0.06 −0.03	
HDG	77.31	107	13.65	±0.02	0.18	±0.02	
GSC	79.68	21	13.96	+0.05 −0.10	0.10	+0.05 −0.10	
SBB	65.74	276	11.55	±0.02	−0.03	±0.02	
CSP	43.05	211	7.72	±0.02	−0.14	±0.02	
PEC	81.91	183	14.16	+0.06 −0.04	−0.07	+0.06 −0.04	Polarity reversed

The error bars assigned to each reading (Tables 1 and 2; Figure 5) were estimated by actually measuring forward and backward from the point on the seismogram picked as the onset to points beyond which the seismogram represented, in our judgment, unambiguous blast energy or unambiguous background noise. Thus, the error bars are, in general, asymmetrical (Figure 3b). The small sizes of most of the error bars can be justified by the small differences between the readings made independently by the USGS and CIT (Figure 3c). The independent readings are in most cases within 0.03 sec of each other. In addition to reading the onset, we read the first peak of each signal, where the first peak was on scale, in an attempt to check, if possible, the consistency of our reading of first arrivals (Figure 5). We were motivated in this effort by the fact that the reading accuracy for first peaks is higher than that for first arrivals; in general, the error is $\pm$ 0.02 to $\pm$ 0.03 sec. If one were to match wave forms at each station from blast to blast in order to improve consistency in reading onsets, one would essentially match first peaks. The result of such an exercise would be the same as reading first peaks rather than reading first arrivals.

We have calculated residuals at each station with respect to travel-time curves

$$\left.\begin{aligned} t &= 1.00+\frac{\Delta}{6.1} \text{ for } Pg \\ t &= 6.20+\frac{\Delta}{8.0} \text{ for } Pn \end{aligned}\right\} \text{ Hector blasts (Figure 4a)}$$

and

$$\left.\begin{aligned} t &= 0.80+\frac{\Delta}{6.1} \text{ for } Pg \\ t &= 6.05+\frac{\Delta}{8.0} \text{ for } Pn \end{aligned}\right\} \text{ Victorville blasts (Figure 4b)}$$

These residuals (Tables 1 and 2) are plotted versus time (Figure 5) with negative residuals, or early arrivals, plotted toward the top of the page so that upward trending curves reflect increasing velocities.

The ray path from Hector to the station BHMH traverses the epicentral area of the Galway Lake earthquake; consequently, this station is very important in the present study. Unfortunately, BHMH was discontinued and replaced by RMR, 8 km to the south, in November 1974. We therefore made a calibration measurement for the Hector blast on August 19, 1975, after the earthquake, by reoccupying the BHMH site. The difference in residuals, Δt (BHMH) $-\Delta t$ (RMR) (see Table 1), for this blast has simply been subtracted from the residuals, Δt (BHMH), for the blasts on July 8, 1974 and August 24, 1974, when only BHMH was operating, in order to extend the curve for RMR (Figure 5a).

The origin times of all earthquakes of magnitude $M_L \gtrsim 4.0$ that occurred within the area 33°20′ to 35°20′N latitude and 115°40′ to 117°50′W longitude (roughly the area of Figure 1) and during the period June 26, 1974 to April 2, 1976 are plotted along with the curves showing temporal change in residual (Figure 5). A number of observations can be made. These are listed below and are separated into observations that are "negative" in character and those that are "positive" in character. Negative observations are the most important results in this study.

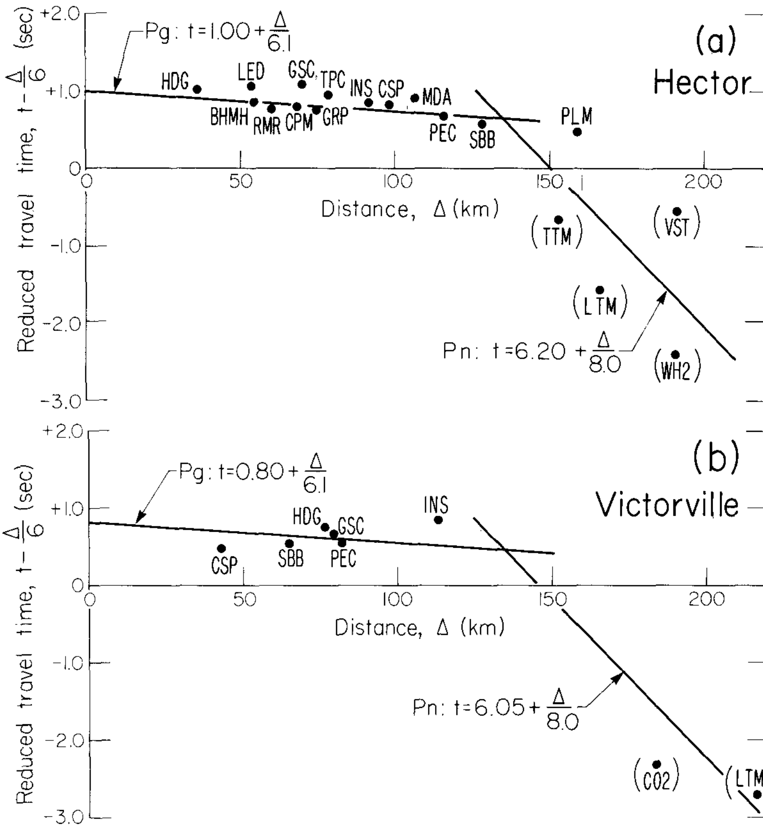

FIG. 4. Reduced travel-time curves for Hector quarry (a) and Victorville quarry (b). Points in parentheses are reduced travel times at stations beyond the area of Figure 1 that were used to establish the *Pn* branches of the curves.

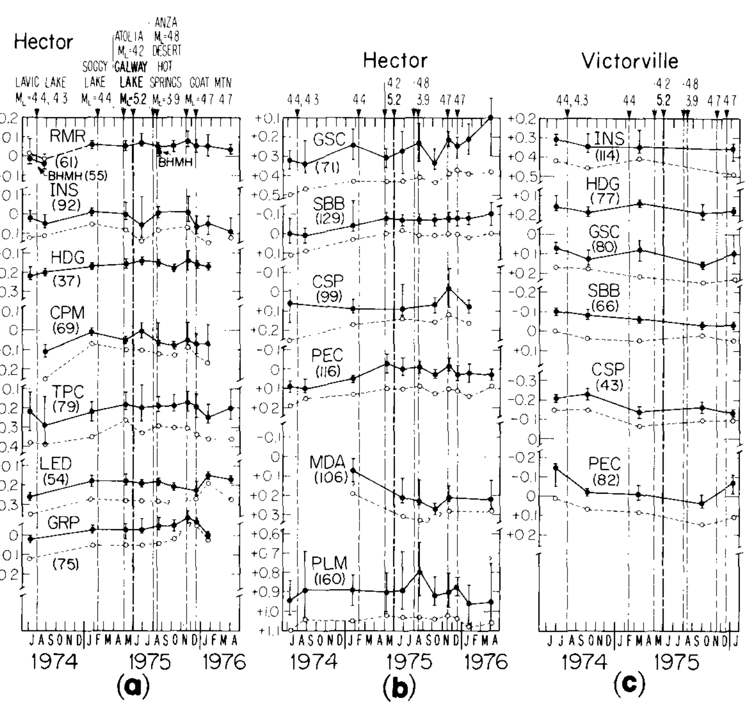

FIG. 5. Temporal variations of residuals for Hector blasts (a) and (b), and Victorville blasts (c). Residuals are plotted with negative residuals toward the top of the page, so that upward trending curves reflect increasing velocity. Numbers in parentheses are approximate quarry station distances in kilometers.

Negative observations

1. No changes greater than about 0.1 sec are seen in any of the curves for the Hector or Victorville blasts. Strictly speaking, no changes greater than about 0.06 to 0.07 sec can be claimed for the Hector curves (see LED and GRP), and no changes greater than 0.03 to 0.04 sec can be claimed for the Victorville curves (see SBB, CSP, and PEC), if one calculates the changes from the top of the lowest error bar to the bottom of the highest error bar. (An exception is the change seen at MDA for Hector blasts; this change derives largely from an anomalous, and somewhat questionable, data point on January 22, 1975). A change of 0.1 sec amounts to at most a change of 1 per cent in average velocity for the stations shown (Figure 5); hence, we can say that there are no changes in average velocity exceeding 1 per cent at any of the recording stations during the 2-year time period of this study.

2. Given the flatness of the curves (Figure 5), it is difficult to draw correlations between earthquakes and changes in residual or velocity. In particular, no correlations are apparent in the cases of the Galway Lake earthquake ($M_L = 5.2$) and Goat Mountain earthquakes ($M_L = 4.7$, 4.7), which are the largest earthquakes that occurred in the area studied (Figure 1) (except for the Anza earthquake, $M_L = 4.8$, which is on the edge of the area of study).

If one examines the curve for RMR for Hector blasts and the curve for HDG for Victorville blasts, one sees no features unique to these curves that can be correlated with the occurrence of the Galway Lake earthquake on June 1, 1975. Yet, the paths from Hector to RMR and from Victorville to HDG pass through the epicentral area of this earthquake at right angles and are the only paths, with the exception of the path from Hector to PLM, that do pass through this area (Figure 1). The data points on January 22, 1975 and May 7, 1975, for the Hector quarry and on March 14, 1975, for the Victorville quarry provide a dense enough sample of the 5-month period before the Galway Lake earthquake to rule out a change in residual of more than 0.1 sec, or a change of average velocity of more than 1 per cent, for any interval of time exceeding 2 months during this period.

No unique features are observable in the curves for INS or CPM for the Hector quarry before the Goat Mountain earthquakes ($M_L = 4.7$ and 4.7) on November 15, 1975 and December 14, 1975. The path from Hector to INS passes through the epicentral area of these earthquakes, and the path from Hector to CPM passes very near (Figure 1). The small bay in the INS curve resulting from a low data point on June 26, 1975, is a suggestive feature that could possibly be correlated with the Goat Mountain earthquakes, but the error bar associated with this point precludes any definitive correlation. (This particular data point poses problems in that INS was unexplainably reversed in polarity during a period of time including this data point. Furthermore, due to instrumental difficulties, it responded very weakly to this blast and to other seismic signals around this date. It was not possible to match wave forms satisfactorily between this blast and previous ones, although the curves in Figure 5 show that spacing between the first arrival and first peak was apparently similar to that in previous blasts.) A period of anomalous velocity of as much as 3 months in duration before the earthquake could have escaped detection in the data at INS but should have been detected in the data at CPM. Average data points are spaced approximately 1 month apart at CPM before the earthquake. Following the first Goat Mountain earthquake, there appears to be a slight drop in velocity at INS which may be correlated with that earthquake. In view of the error bars on the points following this shock, however, a definitive correlation, again, cannot be made.

Positive observations

1. Slight but systematic changes in velocity are observable. Most stations recording Hector blasts show a systematic slight decrease in residual with time, or increase in velocity. Most stations recording Victorville blasts, on the other hand, show an opposite trend.

For Hector blasts an increase in average velocity of as much as 0.8 per cent (0.1 sec at CPM), ignoring error bars for the moment, occurred at a number of stations by January 22, 1975, most notably at CPM, LED, and GRP. At other stations, for example SBB and PEC, the trend continued until May 7, 1975. A couple of stations, namely RMR and HDG, may have peaked slightly later, on June 26, 1975, although the curve for RMR appears essentially flat. Following this rise in average velocity, curves for most stations are flat to the end of the time period represented, although there is some peaking in the curves for LED and GRP and perhaps a decrease in average velocity at INS. The only stations that appear to show different trends are CSP and MDA. The curve for CSP appears flat, although the large error bar on July 8, 1974, leaves open the possibility of an initial rise in average velocity at this station to match that seen at other stations. The curve for MDA is essentially flat, like the curves for the rest of the stations, except for a single anomalous point on January 22, 1975. Although we believe this point has been correctly read, there are some problems with the polarity of the station on this date, and, hence, the point is subject to some question.

For Victorville blasts a more or less linear decrease in average velocity of as much as 0.9 per cent (0.07 sec at CSP), ignoring error bars, occurred at all station shown in Figure 5 during the span of time represented, with the exception that the curve for HDG shows only a negligible decrease, and the curve for PEC shows an increase on January 8, 1976.

2. The curves from reading first-peaks correspond amazingly well in trend with the curves from reading first arrivals. One would expect the wave form to vary somewhat with details of the blasting pattern, such as the total delay in the pattern and spacial dimensions of the pattern. In fact, total delays of the order of 0.01 to 0.05 sec, which are common in the Hector blasts (Table 1), are of the order of the period of peak response (0.07 sec) for the integrated seismometer-Develocorder system for the stations RMR, INS, HDG, CPM, LED, GRP, and MDA; delays of this order of magnitude would be expected to have some effect on the wave form. In any case, the correspondence between the curves for first peaks and for first arrivals lends credence to the trends that are apparent in Figure 5. The correspondence also lends credence to the statements made previously that, disregarding error bars, an initial rise in velocity of as much as 0.8 per cent (e.g., CPM) is observed at all stations for the Hector blasts, and a more or less linear fall in velocity of as much as 0.9 per cent (e.g., CSP) is observed at all stations for Victorville blasts. In cases where error bars are so large as to obscure trends in velocity, such as at GSC and PLM for Hector blasts, the curves for first peaks clarify those trends. At GSC, the curve appears to be rising more or less linearly; at PLM, the curve appears essentially flat. The flat curve at PLM is interesting in that the path from Hector to PLM presumably passes beneath the source region of the Galway Lake earthquake.

Discussion

The curves in Figure 5 show no change in average velocity exceeding 1 per cent along any one of the profiles examined. This result is somewhat disappointing from the point of view of the standard dilatancy model. For the Galway Lake earthquake, $M_L = 5.2$, the dilatancy model predicts a 10 to 20 per cent P velocity decrease over an area several source dimensions in diameter, and over a period of time of 3 to 6 months (Scholz *et al.*, 1973; Whitcomb *et al.*, 1973; Myachkin and Zubkov, 1973). Since the source dimension is about 5 km, the dilatancy model predicts a dimension of the anomalous region about 30 km or so in diameter. Since the distance to RMR is about 60 km, the model would predict a change in the average velocity of about (10 to 20 per cent) × (30/60) = (5 to 10 per cent). The observed change at RMR, which amounts to 0.5 per cent, at the largest between August 24, 1974 and January 22, 1975, is much smaller than the above prediction. If the size of the anomalous region is about the same as that of the aftershock region, then the predicted velocity change becomes 1 to 2 per cent, which is more in line with our observations. The time interval over which we see the anomaly at RMR, such as it is, is also at variance with the standard dilatancy model. An expected 3- to 6-month period of anomalously low velocity followed by a short period of normal velocity prior to the Galway Lake earthquake is ruled out by our data points for January, March, and May, 1975. Since the travel time to RMR falls on a branch of the travel time curve having an apparent velocity of approximately 6 km/sec (Figure 4a), typical of upper crustal velocity, it is very unlikely that the ray path from Hector to RMR remained completely unaffected by the anomalous region, if it existed.

For the Goat Mountain earthquakes, $M_L = 4.7$, 4.7, the dilatancy model predicts a 10 to 20 per cent P velocity decrease over an area perhaps 20 km in diameter, and over a period of time of 2 to 4 months. As above, one calculates the predicted change in velocity at INS to be 2 to 4 per cent. We observed at most 0.4 per cent, if the small bay in that curve is real. The predicted change at CPM would probably be about the same as at INS if the anomalous area were circular. If the anomalous region is about the size of the aftershock region (10 to 15 km), then the change at INS would range from 1 to 3 per cent, and the change at CPM would range from 0 to 1 per cent. A three-month period of anomalous velocity prior to the first Goat Mountain earthquake could have escaped detection at INS, but only a 1-month period could have escaped detection at CPM.

Our data, thus, preclude the possibility of precursory changes as large as predicted by the standard dilatancy model before the Galway Lake and Goat Mountain earthquakes. It is still possible that dilatancy accompanied these earthquakes, but it must have had a small effect. It is also possible that these earthquakes are not representative of other $M_L = 4.7$ to 5.2 earthquakes; however, at least two different types of faulting are represented, namely strike-slip faulting in the case of the Galway Lake earthquake and normal faulting in the case of the first Goat Mountain earthquake.

If dilatancy occurred at all, it must have (a) occurred in very small regions, less than or equal in size to the aftershock regions of these 2 earthquakes; (b) had a very small effect, resulting in less than about 3 to 4 per cent change in velocity in the dilatant regions, if these regions had dimensions as large as predicted; or (c) occurred during very short time periods, namely less than 2 months in the case of the Galway Lake earthquake and less than 1 month in the case of the Goat Mountain earthquakes.

McEvilly and Johnson (1973) used many quarry blasts in central California for the purpose of detecting possible premonitory velocity changes associated with strike slip earthquakes. They found no velocity change correlatable with earthquakes. They suggested that either the dilatancy effect is not significant for these earthquakes, or if dilatancy occurred at all, the anomalous area must have been so small that the total effect was too small to be detected. Cramer and Kovach (1974) arrived at similar conclusions for the Bear Valley ($M = 5.1$, 1972) and San Juan Bautista ($M = 4.9$, 1972) earthquakes. Our results support these conclusions. Using earthquakes as sources, Robinson *et al.* (1974) found a significant velocity change before the 1972 Bear Valley earthquake in central California for which McEvilly and Johnson (1973) and Cramer and Kovach (1974) found no positive evidence; however, the anomaly appears to have been small in both space and time. These results have been questioned recently, however (Wesson *et al.*, 1976), and it is possible that there was no anomaly before the Bear Valley event. As noted earlier, an anomaly prior to the Bear Valley event may have been restricted to a volume of about the same diameter as the aftershock region, 14 km, and the time interval for the anomaly was about 1 month, about half the value suggested by other investigators for an earthquake of magnitude 5 (Scholz *et al.*, 1973; Whitcomb *et al.*, 1973). As noted earlier, an anomaly period as short as 1 month for the Galway Lake earthquake ($M_L = 5.2$) might have escaped detection, although this seems rather unlikely in view of the monotonous character of the curves.

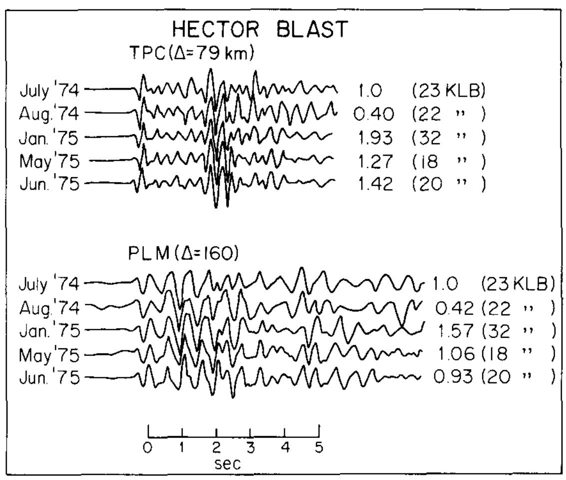

FIG. 6. Wave forms of Hector blasts at stations TPC and PLM. Numbers to the right of each trace indicate the relative amplitude; numbers in parentheses, the yields of the blasts.

It might also be argued that a marked velocity change did happen in the source region, but that, because of some unfavorable structural condition in the area, the direct seismic rays did not actually sample the anomalous region. This possibility seems remote on the basis of the wave-form comparison at PLM and TPC, as shown in Figure 6. The path from Hector to PLM goes through the epicentral region. If the anomalous region is about 30 km in diameter, and a velocity change of 10 to 20 per cent occurred there, a delay of about 1 sec is expected for waves which travel through this region. The anomalous region must significantly affect the travel time of one of the later phases, if not the first arrival. However, the wave form for the 7 sec following the first arrival at PLM correlates very well from event to event, and there is no indication of such a delay. The same is true of wave forms at TPC (Figure 6). Unfortunately, high amplitudes in the Hector blast records at RMR (Figure 3a) do not permit comparison of wave forms at this station.

On Develocorder films, the first arrivals can be picked with an accuracy of 0.02 sec at stations with $\Delta \leqq 75$ km. The WWVB radio signals are recorded on the top and bottom traces of the film (see Figure 3a). Because of the distortion due to the optical system, film, and galvanometer offsets, the signal trace is sometimes offset with respect to the radio trace. This offset causes a reading error of as much as 0.02 sec. Another annoying source of error are the delays in the telephone lines (including various relaying circuits) used for the telemetry. Although we have not looked into this problem in detail, preliminary measurements indicate delays of 0.02 to 0.07 sec. Whether or not this delay is time-dependent is not yet clear. If the delay is not time-dependent this source of error is not important in our results. If it is time-dependent, the fluctuation may be considered random. It is, furthermore, not clear how delays vary from telephone line to telephone line. For the record, the stations discussed herein are grouped as follows on telephone lines: RMR-HDG-CPM-INS; TPC; LED-GRP; GSC; SBB; CSP-PEC; MDA; PLM. If all line delays are similar, then this source of error is not important in our results. In the worst case, where all of these potential errors are additive, the error of an individual reading can be as large as 0.06 to 0.11 sec, which is of the order of the maximum change observed for the Hector blasts. The fact that stations on different Develocorders and different telephone lines all show similar trends in velocity suggests that Develocorder distortions and telephone line delays are not responsible for these trends.

Two possible explanations for the systematic trends seen in the Hector and Victorville data are the following: (1) there were systematic variations in local delays at the two quarries, (2) there were regional changes in crustal velocity. Perhaps there are other explanations as well.

Shot points for Hector blasts show a systematic migration from northwest to southeast in the quarry (Figure 2a). Most of the increase in average velocity, amounting to a decrease in residual of up to 0.1 sec, occurred between July 8, 1974 and May 7, 1975. The shot points on these two dates are separated by about 90 m. The maximum local delay one would expect from this separation would be of the order of the maximum separation divided by local quarry velocity or 0.090 km/1.5 km/sec = 0.06 sec. (Bentonite is quarried at Hector; a sample was determined in the laboratory at CIT to have a velocity of 1.5 km/sec.) Thus, local delays in the quarry could conceivably explain the trend in the data between July 8, 1974 and May 7, 1975. It is, however, somewhat surprising that the much larger separation (300 meters) between the shot points on May 7, 1975 and April 2, 1976, produced no further noticeable trend in the data. Nevertheless, the systematic trend in shot-point location and the systematic trend in the data do suggest a cause-and-effect relationship.

Shot points for Victorville blasts also show a more or less systematic migration to the southeast (Figure 2b). The maximum local delay expected between June 26, 1974 and January 8, 1976 would probably range from (0.22 km)/4 to 6 km/sec = 0.06 to 0.04 sec. (Marble is quarried at Victorville quarry.) Thus, at Victorville also, local delays in the quarry could explain the trend in the data.

The possibility that the trends in the quarry data reflect regional changes in crustal velocity is intriguing. At stations at all azimuths from Hector quarry one sees an increase in average velocity over the period of July 8, 1974 to April 2, 1976, although in detail the increase is largely confined to the period prior to May 7, 1975. At stations at all azimuths from Victorville quarry, one sees a decrease in average velocity over about the same period of time. The opposite trends for Hector and Victorville data is somewhat puzzling unless adjacent regions, one surrounding Hector quarry and one surrounding Victorville quarry, are simultaneously undergoing opposite changes in velocity. To check this possibility, one would like to examine paths from the two quarries that traverse similar areas of the crust. Station-to-epicenter distances should be similar to insure that the rays are penetrating the same depths in the crust (refer to Figure 4, a and b). The paths from Hector to CSP and from Victorville to HDG come close to satisfying these criteria. Indeed, curves for both of these paths are similar in that they are relatively flat (Figure 5), although there is some question whether or not the curve for CSP initially rises. These two curves stand out somewhat from other curves in the Hector and Victorville groups in that neither shows strongly the trends seen in the rest of their respective groups. The paths from Hector to PEC and Victorville to INS satisfy less well the above criteria. Curves for these paths do show opposite trends that would seem contradictory. The path from Victorville to SBB is close to the path from Hector to SBB, throughout its length, but station-to-epicenter distances are quite different. The curves for these two paths show strongly opposite trends that would seem contradictory; however, the ray from Hector to SBB may be traveling deeper in the crust. (The wave form at SBB from Hector blasts suggests refraction along a deep layer.)

It is, thus, difficult to evaluate the possibility that two adjacent regions of the crust are undergoing opposite trends in velocity. However, the occurrence of numerous larger earthquakes, including the Galway Lake earthquake, the Goat Mountain earthquakes, and others (Figure 1), in a region nearer to Hector quarry and the simultaneous absence of larger earthquakes in the region of the Victorville quarry is intriguing. Perhaps the occurrence of earthquakes is somehow related to rising velocities near Hector, if they are indeed rising. Such a correlation is reasonable if the velocity increase is due to tectonic stress loading as suggested by Sassa (1948), Hayakawa (1950), and more recently by Eisler (1967, 1969).

The sensitivity of velocity to stress in *in situ* crustal rocks is not well known. Eisler (1967) suggests a fairly large value of 2×10^{-3} km/sec-bar (Figure 1 of Eisler, 1967) for stresses less than 0.5 kbar, that decreases sharply as stress increases. De Fazio *et al.* (1973), and Reasenberg and Aki (1974) found a very high sensitivity of 0.2 per cent per bar for *in situ* rocks, attributing it to the presence of extremely thin cracks in the rock. This sensitivity may drop significantly at depth, but the pattern of decrease is unknown. Since the stress drop associated with earthquakes is considered to be 10 to 100 bars, the observed velocity change of about 1 per cent is not unreasonable in the light of the experimental values quoted above.

Conclusion

The standard version of the dilatancy model of earthquakes predicts a *P*-wave velocity decrease of 10 to 20 per cent before an earthquake. For an $M_L = 5.2$ earthquake, such as the Galway Lake earthquake, this velocity decrease should occur over an area about 30 km in diameter over a period of 3 to 6 months before the earthquake. For an $M_L = 4.7$ earthquake, such as the Goat Mountain earthquakes, the velocity decrease should occur over an area about 20 km in diameter over a period of 2 to 4 months. The precise travel-time data obtained from blasts at the Hector and Victorville quarries preclude the possibility of precursory changes this large before the Galway Lake and Goat Mountain earthquakes. It is still possible that dilatancy accompanied these earthquakes, but the effect must have been small. It is also possible that these earthquakes are not representative of other $M_L = 4.7$ to 5.2 earthquakes; however, at least two different types of faulting are represented, namely, strike slip and normal faulting.

If dilatancy occurred at all, it must have (a) occurred in very small regions, less than or equal in size to the aftershock regions of these two earthquakes, (b) had a very small effect, resulting in less than about 3 to 4 per cent change in velocity in the dilatant regions, if these regions had dimensions as large as predicted, or (c) occurred during very short time periods, namely less than 2 months in the case of the Galway Lake earthquake and less than 1 month in the case of the Goat Mountain earthquakes. This conclusion supports the findings of McEvilly and Johnson (1973), Cramer and Kovach (1974), and Boore *et al.* (1975) that there is no positive evidence for significant velocity change before earthquakes.

Although the relatively large velocity changes predicted by the dilatancy model are not found in this study, small changes are, in fact, found. Stations at all azimuths from Hector quarry show a temporal increase in velocity of as much as 0.8 per cent, most of which appears to have occurred during the initial 6 months of the 2-year period studied. Stations at all azimuths from Victorville quarry show a temporal decrease in velocity of as much as 0.9 per cent. Two explanations for these systematic trends are that (1) there were systematic variations in local delays at the two quarries, and (2) there were regional changes in crustal velocity. The fact that shot points migrated in more or less systematic fashions in both Hector and Victorville quarries suggests that the first explanation may be correct. The second explanation is intriguing, but the opposite trends for the Hector and Victorville data are somewhat puzzling, unless adjacent regions, one surrounding Hector quarry and one surrounding Victorville quarry, are simultaneously undergoing opposite changes in velocity. This possibility is difficult to evaluate. One can observe, however, that during the 2-year period of this study all larger earthquakes are concentrated in the region of the Hector quarry, and there is simultaneously an absence of larger earthquakes in the region of the Victorville quarry. Perhaps the occurrence of larger earthquakes is related to rising velocities near Hector, if they are indeed rising. Such a correlation is reasonable if the velocity increase is due to tectonic stress loading as suggested by Sassa (1948), Hayakawa (1950), and Eisler (1967, 1969).

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SEISMOLOGICAL LAB.
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA 91125 (H.K.)
DIVISION OF GEOLOGICAL AND PLANETARY SCIENCES
CONTRIBUTION NO. 2678

U.S. GEOLOGICAL SURVEY
PASADENA, CALIFORNIA 91125 (G.F.)

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